Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
12 (2008) 1562–1587

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Renewable building energy systems and passive human comfort solutions

Abdeen Mustafa Omer*

17 Juniper Court, Forest Road West, Nottingham NG7 4EU, UK

Received 31 May 2006; accepted 31 July 2006

Abstract

With environmental protection posing as the number one global problem, man has no choice but to reduce his energy consumption. One way to accomplish this is to resort to passive and low-energy systems to maintain thermal comfort in buildings. The conventional and modern designs of wind towers can successfully be used in hot arid regions to maintain thermal comfort (with or without the use of ceiling fans) during all hours of the cooling season, or a fraction of it. Climatic design is one of the best approaches to reduce the energy cost in buildings. Proper design is the first step of defence against the stress of the climate. Buildings should be designed according to the climate of the site, reducing the need for mechanical heating or cooling. Hence maximum natural energy can be used for creating a pleasant environment inside the built envelope. Technology and industry progress in the last decade diffused electronic and informatics' devices in many human activities, and also in building construction. The utilisation and operating opportunities components, increase the reduction of heat losses by varying the thermal insulation, optimise the lighting distribution with louver screens and operate mechanical ventilation for coolness in indoor spaces. In addition to these parameters the intelligent envelope can act for security control and became an important part of the building domotic revolution. Application of simple passive cooling measure is effective in reducing the cooling load of buildings in hot and humid climates. Fourty-three percent reductions can be achieved using a combination of well-established technologies such as glazing, shading, insulation, and natural ventilation. More advanced passive cooling techniques such as roof pond, dynamic insulation, and evaporative water jacket need to be considered more closely. The building sector is a major consumer of both energy and materials worldwide, and that consumption is increasing. Most industrialised countries are in addition becoming more and more dependent on external supplies of conventional energy carriers, i.e., fossil fuels. Energy for heating and cooling can be replaced by new renewable energy sources. New renewable energy sources, however, are usually not

*Tel.: +44 115 978717.
E-mail address: abdeenomer2@yahoo.co.uk.

1364-0321/$ - see front matter
doi:10.1016/j.rser.2006.07.010

economically feasible compared with the traditional carriers. In order to achieve the major changes needed to alleviate the environmental impacts of the building sector, it is necessary to change and develop both the processes in the industry itself, and to build a favourable framework to overcome the present economic, regulatory and institutional barriers. This article describes various designs of low-energy buildings. It also, outlines the effect of dense urban building nature on energy consumption, and its contribution to climate change. Measure, which would help to save energy in buildings, is also presented.

Keywords: Built environment; Energy savings in buildings; Energy-efficient comfort; Climate change

Contents

1. Introduction

Natural resources may be renewable, non-renewable or abstract. Non-renewable resources include fossil fuels, minerals, clear-felled tropical hardwoods that are not replaced and rare animals or plants that are hunted or collected in an uncontrolled way. Renewable resources include energy from the sun and the biological and biogeochemical cycles (such as the water and energy hydrological and carbon cycle). At a more immediate level, renewable resources include forests that have been selectively felled and replanted, animal and plant populations that have been properly managed through controlled hunting, fishing and collecting, and waters with controlled inputs that can be readily recycled and reused. Abstract resources include animals, plants and the natural landscape as part of ‘the countryside’ used for recreation and tourism activities such as bird watching, fishing, hiking, sight-seeing, etc. Non-renewable resources are of course finite, while the other two categories are effectively infinite. Our

descendants will not thank us for exhausting finite resources, nor for destroying the renewable ones.

In many countries, global warming considerations have led to efforts to reduce fossil energy use and to promote renewable energies in the building sector. Energy use reductions can be achieved by minimising the energy demand, by rational energy use, by recovering heat and cold and by using energy from the ambient air and from the ground. To keep the environmental impact of a building at sustainable levels (e.g., by greenhouse gas neutral emissions), the residual energy demand must be covered with renewable energy. In this theme integral concepts for buildings with both excellent indoor environment control and sustainable environmental impact are presented. Special emphasis is put on ventilation concepts utilising ambient energy from air ground and other renewable energy sources, and on the interaction with heating and cooling. It is essential to avoid the need for mechanical cooling, e.g., by peak load cutting, load shifting and use of ambient heat or cold from air or ground. Techniques considered are hybrid (controlled natural and mechanical) ventilation including night ventilation, thermo-active building mass systems with free cooling in a cooling tower, and air intake via ground heat exchangers. For both residential and office buildings, the electricity demand remains one of the crucial elements to meet sustainability requirements. The electricity demand of ventilation systems is related to the overall demand of the building and the potential of photovoltaic systems and advanced co-generation units.

The heating or cooling of a space to maintain thermal comfort is a highly energy intensive process accounting for as much as 60–70% of total energy use in non-industrial buildings. Of this, approximately 30–50% is lost through ventilation and air infiltration. However, estimation of the energy impact of ventilation relies on detailed knowledge of air change rates and the difference in enthalpy between the incoming and outgoing air streams. In practice, this is a difficult exercise to undertake as there is much uncertainty about the value of these parameters [1]. As a result, a suitable datum from which strategic planning for improving the energy efficiency of ventilation can be developed has proved difficult to establish [1]. Efforts to overcome these difficulties are progressing in the following two ways:

- Identifying ventilation rates in a representative cross section of buildings.
- The energy impact of air change in both commercial and domestic buildings.

In addition to conditioning energy, the fan energy needed to provide mechanical ventilation can make a significant further contribution to energy demand. Much depends on the efficiency of design, both in relation to the performance of fans themselves and to the resistance to flow arising from the associated ductwork.

The building sector is an important part of the energy picture. Note that the major function of buildings is to provide an acceptable indoor environment, which allows occupants to carry out various activities. Hence, the purpose behind this energy consumption is to provide a variety of building services, which include weather protection, storage, communications, thermal comfort, facilities of daily living, aesthetics, work environment, etc. However, the three main energy-related building services are space conditioning (for thermal comfort), lighting (for visual comfort), and ventilation (for indoor air quality). Pollution-free environments are a practical impossibility. Therefore, it is often useful to differentiate between unavoidable pollutants over which little source control is possible, and avoidable pollutants for which control is possible. Unavoidable

pollutants are primarily those emitted by metabolism and those arising from the essential activities of occupants. 'Whole building' ventilation usually provides an effective measure to deal with the unavoidable emissions, whereas 'source control' is the preferred, and sometimes only practical, method to address avoidable pollutant sources [1]. Hence, achieving optimum indoor air quality relies on an integrated approach to the removal and control of pollutants using engineering judgment based on source control, filtration, and ventilation. Regardless of the kind of building involved, good indoor air quality requires attention to both source control and ventilation. While there are sources common to many kinds of buildings, buildings focusing on renewable energy may have some unique sources and, therefore, may require special attention [1]. In smaller (i.e., house size) buildings, renewable sources are already the primary mechanism for providing ventilation. Infiltration and natural ventilation are the predominant mechanisms for providing residential ventilation for these smaller buildings.

Ventilation is the building service most associated with controlling the indoor air quality to provide a healthy and comfortable environment. In large buildings ventilation is normally supplied through mechanical systems, but in smaller ones, such as single-family homes, it is principally supplied by leakage through the building envelope, i.e., infiltration, which is a renewable resource, albeit unintendedly so. Ventilation can be defined as the process by which clean air is provided to a space. It is needed to meet the metabolic requirements of occupants and to dilute and remove pollutants emitted within a space. Usually, ventilation air must be conditioned by heating or cooling in order to maintain thermal comfort and, hence, becomes an energy liability. Indeed, ventilation energy requirements can exceed 50% of the conditioning load in some spaces [1]. Thus, excessive or uncontrolled ventilation can be a major contributor to energy costs and global pollution. Therefore, in terms of cost, energy, and pollution, efficient ventilation is essential. On the other hand, inadequate ventilation can cause comfort or health problems for the occupants. Good indoor air quality may be defined as air, which is free of pollutants that cause irritation, discomfort or ill health to occupants [2]. Since a long time is spent inside buildings, considerable effort has focused on developing methods to achieve an optimum indoor environment. Achieving energy efficiency and optimum Indoor Air Quality (IAQ) depends on minimising the emission of avoidable pollutants. Pollutants inside buildings are derived from both indoor and outdoor contaminant sources.

2. Environment pollutions

The multifaceted role of present-day environmental engineers demands a greater understanding of the functioning of living systems and of their interaction with the environment on which the work of the engineer is based. As shown in Fig. 1 the physical and chemical (Abiotic) components are one part of the natural environment, while the biotic component is living organisms that provide well being of the human species and the earth as whole.

Table 1 lists the significant directives. The list is meant to give an idea of the range of directives and is not meant to be comprehensive. The significant 'environments' are: water, air and land (soil). The criteria air pollutants (ambient air standards) and some limits and associated directives are listed in Table 2. It is noted from Table 2 that not all criteria pollutants have EU ambient limit values. The direct and indirect effect is to

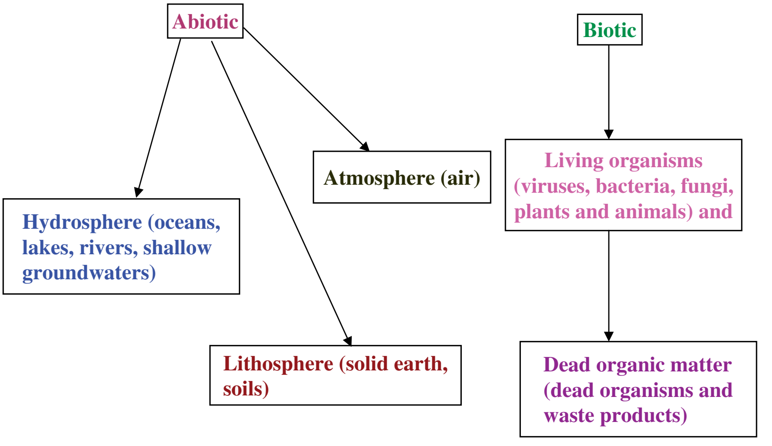


Fig. 1. The major components and subcomponents of the natural environment.

Table 1
Significant EU environmental directives in water, air and land environments

Environment	Directive name
Water	Surface water for drinking
	Sampling surface water for drinking
	Drinking water quality
	Quality of freshwater supporting fish
	Shellfish waters
	Bathing waters
	Dangerous substances in water
	Groundwater
	Urban wastewater
	Nitrates from agricultural sources
Air	Smokes in air
	Sulphur dioxide in air
	Lead in air
	Large combustion plants
	Existing municipal incineration plants
	New municipal incineration plants
	Asbestos in air
	Sulphur content of gas oil
	Lead in petrol
	Emissions from petrol engines
	Air quality standards for NO_2
	Emissions from diesel engines
Land	Protection of soil when sludge is applied

be described on:

- material and cultural heritage;
- human beings, fauna and flora;
- soil, water, air, climates and landscape.

Table 2
EU criteria pollutant standards in the ambient air environment

Pollutant	EU limit
CO	30 mg/m^2; 1 h
NO_2	200 μg/m^2; 1 h
O_3	235 μg/m^2; 1 h
SO_2	250–350 μg/m^2; 24 h
	80–120 μg/m^2; annual
PM_{10}	250 μg/m^2; 24 h
	80 μg/m^2; annual
$SO_2 + PM_{10}$	100–150 μg/m^2; 24 h
	40–60 μg/m^2; annual
Pb	2 μg/m^2; annual
Total suspended particulate (TSP)	260 μg/m^2; 24 h
HC	160 μg/m^2; 3 h

Other areas addressed in directives that are of relevance to environmental engineering/science include: Noise, habitats, and general.

Natural living systems supply humanity with an array of indispensable and irreplaceable services that support our life on earth [3]. These include direct resources such as building products (wood), food, medicines, clothing materials, etc. Living systems also provide functional services such as maintenance of the appropriate mix of atmospheric gases, generation and preservation of soils, disposal of wastes, restoration of systems following disturbance, control of pests, cycling of nutrients and pollination of crops. Thus, not only is humanity totally dependent on the living environment but also the integrity of the planet is itself dependent on the maintenance of the natural environment and on the interactions between the living organisms and the physical/chemical components of the earth.

3. Methods of expressing concentration

The methods of expressing the concentration of a constituent of a liquid or gas are:

(1) Mass/volume: The mass of solute per unit volume of solution (in water chemistry). This is analogous to weight per unit volume, typically, mg/L = ppm (parts per million).
(2) Mass/mass or weight/weight: The mass of a solute in a given mass of solution, typically, mg/kg or ppm (parts per million).

If the density of a solution = ρ = mass of solution/volume of solution (kg/L) and, concentration of a constituent in mg/L = C_{A1} = mass of constituent/volume of solution (mg/L), and, concentration of a constituent in ppm = C_{A2} = mass of constituent/mass of solution (mg/kg).

Then rearranging,

$$\rho = C_{A1}/C_{A2}.$$

$$\text{If } \rho = 1\,\text{kg/L}, \quad \text{then } C_{A1} = C_{A2}, \tag{1}$$

i.e., the concentration of a constituent in ppm mg/kg = concentration of a constituent in mg/L.

For most applications in water and wastewater environments, $\rho = 1\,\text{kg/L}$. For applications in the air environment, Eq. (1) does not hold. The use of mg/L is most common in water applications as the volume of the solution is usually determined as well as the mass of the solute. The unit ppm is typically used in sludges or sediments.

To prove the portable of transmutation of pollutants, experimental investigations may be conducted to bombard C or CO_2 or CH_4 or other air pollutants by accelerated alpha particles in a low-pressure vacuum tube in a similar condition of ionosphere. Heating them with gamma radiation can accelerate the alpha particles. The results of such experimental investigation may prove the probable transmutation of pollutants and self-sustaining equilibrium of the global environment [6].

4. Population

This consists of a group of individuals of the same species living in a particular area at the same time. Each population is genetically distinct to some degree from other separate populations of the same species. They have a size and a birth, death and hence population growth rate. Populations of different species live together, many interacting with each other, forming a community, e.g., in a pond—a natural community of plants, animals and microbes forming a distinctive living system.

The 'greenhouse effect' is but one of the environmental problems that have resulted either directly or indirectly from the activities of man. The role of the human population on environmental change has been simply summarised by Erlich [3] in the simplified equation:

$$I = PAT, \tag{2}$$

where the impact I of the population on the environment results from the size of the population (P), the *per capita* affluence or consumption (A) and the damage caused by technologies (T) employed to supply each unit of consumption. As P increases, so too does T because supplies to additional people must be mined from deeper ores, pumped from deeper deposits, transported further. It is also suggested that the *per capita* consumption of commercial energy in a nation can be used as a surrogate for the AT part of the equation—a considerable proportion of the environmental damage involves use of commercial energy, from cleaning tropical forests for agriculture to mining, manufacturing, road building and extraction of fossil fuels [3].

The overall human population has more than doubled in the past 40 years although not evenly over the globe. Population growth rates are increasing exponentially in the less/underdeveloped countries while growth is slow or non-existent in most developed countries. Many resources are being depleted with little recycling, and waste products are being returned to the environment in a different form and at concentrations that are often toxic or otherwise damaging. Land use changes are taking place rapidly. The global human population lives on only about 2 per cent of the global land area, but a further 60 per cent is taken up growing crops, grazing livestock or being utilised for extraction of mineral resources and removal of forest. Much of the remaining land area either desert or covered with ice or is too steep for use [4]. Forests, grasslands and wetlands are disappearing rapidly and deserts are expanding due to soil erosion and a decline in underground water deposits and lowering of water tables. Human activity is therefore seen as a significant cause of environmental change, mainly as a result of the conflict between maintaining and

using the environment, i.e., development and exploitation of physical resources, building and urbanisation, changing land use and deposition of wastes, often at the expense of the integrity of the biotic component of the environment and biological resources.

5. Energy-efficient comfort

In warm humid conditions, airflow can be an energy-efficient means to achieve indoor thermal comfort. Airflow does not create sensible cooling of air that can be measured on a thermometer; it conducts heat from our skin. This results in a cooling sensation ASHRAE [5]. This cooling sensation becomes noticeable with uniform airflow above 0.2 m/s, while airflow greater than 1.0 m/s begins to disturb loose papers. This discourages utilisation of airflow greater than 1.0 m/s in office-type spaces. Airflow up to 2.0 m/s is frequently provided in industrial and storage buildings as well as living areas and bedrooms in houses in hot humid climates. Many studies, ASHRAE [5] have modelled the cooling sensation of uniform airflow on human thermal response. In steady airflow, the cooling sensation (CS), of airflow can be estimated in degrees Celsius using equation:

$$\mathrm{CS} = 3.67(V - 0.2) - (V - 0.2)^2\,{}^\circ\mathrm{C}, \tag{3}$$

when average airflow, V, is in m/s.

Natural ventilation from breezes or difference in air temperature generated by solar chimneys can induce passive indoor airflow. The problem with a passive approach is that breezes are not always present when needed and solar chimneys rarely produce enough airflow for comfort. Fans, particularly ceiling fans, can provide a reliable source for airflow for indoor thermal comfort in warm humid environments. Unsteady airflow, with an appropriate gust frequency, can enhance the cooling sensation of airflow. Airflow provides a cooling sensation for occupants of buildings in warm humid climates. The enhanced benefits of turbulent airflow, with gust velocities within the range of 0.3 to 0.5 Hz (with a peak preference at 0.47 Hz), present further opportunities to utilise large, high-volume, low-speed ceiling fans for energy efficient cooling. This effect appears to be due to a peak response of human cold cutaneous thermoreceptors just beneath the skin.

As an alternative and new design philosophy, hybrid ventilation and cooling technologies (HVAC) combine the advantages of mechanical HVAC systems and natural ventilation. It has the potential to reduce energy consumption in many buildings, improve the satisfaction level of the occupants' comfort and minimise the sick building syndromes (SBS). Hybrid ventilation and cooling provides opportunities for innovative solutions to the problems of energy-consuming environment control in buildings. Because hybrid systems combine natural and mechanical ventilation, they present several complex challenges to design and analysis tools, requiring a global approach that takes into account the outdoor environment, the indoor environment, control strategy and the mechanical system.

6. Wind towers

Operation of conventional wind towers or Baud-Geers achieved summer comfort in the hot arid regions. Wind towers maintain natural ventilation through buildings due to wind or buoyancy effects. The tower structure is cooled externally through radiative transfer with the sky, and internally with the cool ambient air, circulated through the building and the tower during the night. During the day, the warm ambient air is partially cooled by

tower structure before entering the building. When passed over moist surfaces air is cooled evaporatively. However, sensible and evaporative cooling potentials of conventional wind towers, which depend on the tower design, are limited. Another disadvantage of the conventional wind tower is the admittance of dust into the building. Two modern designs of wind towers are considered which eliminate the above disadvantages. One design incorporates one-way dampers in the tower head and a wetted column in the tower. This design, which is particularly suitable in areas with good winds, evaporatively cools the hot-dry ambient air before admitting it into the building. The other design incorporates evaporative cooling pads at the tower entrance. This design is particularly suitable in areas with very little or no winds.

With the advent of mechanical or chemical cooling systems, the use of Baud-Geers in new buildings has been greatly reduced. The use of evaporative or desert coolers and mechanical air conditioners is now very common. The major advantage of wind towers or Baud-Geers is that they are passive systems, requiring no energy for their operation. Major disadvantages of the conventional wind towers may be summarised as follows:

- Dust and insects can enter the building.
- A portion of the air admitted in the tower is lost through other tower openings and never enters the building. When the tower has only opening facing the wind, all the air entering the tower enters the house.
- The amount of coolness which can be stored in the tower mass is generally limited (due to small mass and low specific heat of the energy-storing material), and may not be enough to meet the cooling needs of the building during hot summer days.
- The evaporative cooling potential of the air is not fully utilised.
- Baud-Geers do not find any application in areas with very low wind speeds.

Modern designs of wind towers are briefly discussed below:

(1) Wind towers with evaporative cooling column: This design consists of three distinct improvements. The height and the total cross-sectional area of the column can be selected to produce a desired airflow rate and temperature to meet the level of thermal comfort needed in a building.

- A tower head, which accepts wind blowing in any direction and prevents the air from leaving the other tower openings.
- A column with a substantial increase in the heat and mass transfer areas.
- Full utilisation of the potential of evaporative cooling of air by wetting the wall areas of the column.

(2) Wind towers with evaporative cooling pads placed at the tower entrance: In areas with little or no winds, the entire opening area of the wind tower head can be covered with evaporative cooling pads. The air circulation through the tower and the building is accomplished through buoyancy effects. This design finds applications in areas with low winter heating needs [7].

With environmental protection posing as the number one global problem, man has no choice but reducing energy consumption. One way to accomplish this is to resort to passive and low-energy systems to maintain thermal comfort in buildings. The conventional and modern designs of wind towers can successfully be used in the hot arid regions to maintain

thermal comfort (with or without the use of ceiling fans) during all hours of the cooling season, or a fraction of it.

7. Bioclimatic design

Bioclimatic design cannot continue to be a side issue of a technical nature to the main architectural design. In recent years started to alter course and to become much more holistic in its approach while trying to address itself to:

- the achievement of a sustainable development;
- the depletion of non-renewable sources and materials;
- the life cycle analysis of buildings;
- the total polluting effects of buildings on the environment;
- the reduction of energy consumption and;
- human health and comfort.

Hidden dimensions of architectural creation are vital to the notion of bioclimatic design. The most fundamental ones are:

TIME, which has been called the fourth dimension of architectural space, is of importance because every object cannot exist but in time. The notion of time gives life to an object and releases it to periodic (predictable) or unperiodic repetition. Times relates to seasonal and diurnal patterns and thus to climate and the way that a building behaves or should be designed to couple with and not antagonise nature. It further releases to the dynamic nature of a building in contrast to the static image that we have created for it.

AIR, is a second invisible but important element. We create space and pretend that it is empty, oblivious of the fact that it is both surrounded by and filled with air. Air in its turn, due to air-movement, which is generated by either temperature or pressure differences, is very much there and alive. And related to the movement of air should be building shapes, sections, heights, orientations and the size and positioning of openings.

LIGHT, and in particular daylight, is a third important element. Architecture cannot exist but with light and from the time we have been able to substitute natural light with artificial lighting, many a building and a lot of architecture has become poorer so. It is not an exaggeration to say that the real form giver to architecture is not the architect himself but light and that the architect is but the form moulders.

Vernacular architecture is beautiful to look at as well as significant to contemplate on. It is particularly interesting to realise the nature of traditional architecture where various devices to attain thermal comfort without resorting to fossil fuels can be seen. Sun shading and cross ventilation are two major concerns in house design and a south-facing façade is mandatory to harness the sun in winter as much as possible. Natural ventilation required higher ceilings to bring a cooling effect to occupants in buildings built 50 years ago, whereas modern high technology buildings have lower ceiling heights, thus making air conditioning mandatory. Admitting the human right of enjoying modern lives with a certain level of comfort and convenience, it is necessary to consider how people can live and work in an ideal environment with the least amount of energy consumption in the age of global environment problems. People in the modern age could not put up with the poor indoor environment that people in the old age used to live in. In fact, in those days people

had to live with the least amount of fuels readily available and to devise various means of constructing their houses so that they would be compatible with the local climate. It is important, therefore, in designing passive and low-energy architecture for the future to learn from their spirit to overcome difficulties by having their creative designs adapted to respective regional climatic conditions and to try to devise the ecotechniques in combination with a high grade of modern science.

8. Relationship between climate, building and occupants

In climate-sensitive architecture, strategies are adopted to meet occupants' needs, taking into account local solar radiation, temperature, wind and other climatic conditions. Different strategies are required for the various seasons. These strategies can themselves be subdivided into a certain number of concepts, which represent actions.

The heating strategy includes four concepts (Fig. 2):

- solar collection: collection of the sun's heat through the building envelope;
- heat storage: storage of the heat in the mass of the walls and floors;
- heat distribution: distribution of collected heat to the different spaces, which require heating;
- heat conservation: retention of heat within the building.

The cooling strategy include five concepts (Fig. 3):

- solar control: protection of the building from direct solar radiation;
- ventilation: expelling and replacing unwanted hot air;
- internal gains minimisation: reducing heat from occupants, equipments and artificial lighting;
- external gains avoidance: protection from unwanted heat by infiltration or conduction through the envelope (hot climates);
- natural cooling: improving natural ventilation by acting on the external air (hot climates).

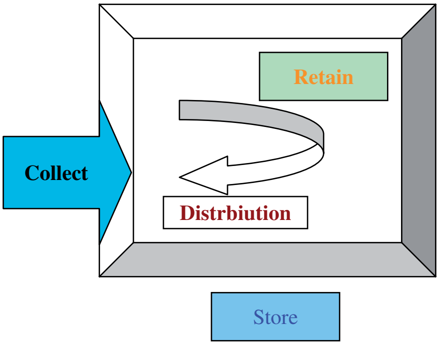


Fig. 2. Heating strategy.

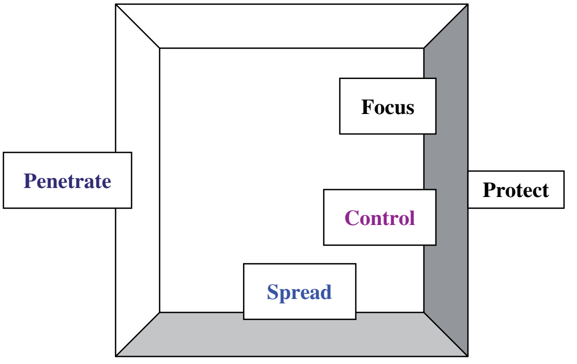


Fig. 3. Cooling strategy.

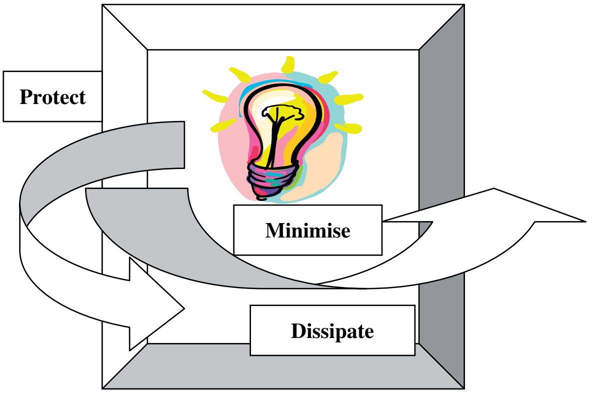


Fig. 4. Daylighting strategy.

The daylighting strategy includes four concepts (Fig. 4):

- penetration: collection of natural light inside the building;
- distribution: homogeneous spreading of light into the spaces or focusing;
- protect: reducing by external shading devices the sun's rays penetration into the building;
- control: control light penetration by movable screens to avoid discomfort.

Ventilation is essential for securing a good indoor air quality, but, as explained earlier, can have a dominating influence on energy consumption in buildings. Air quality problems are more likely to occur if air supply is restricted. Probably a ventilation rate averaging 7 l/s p represents a minimum acceptable rate for normal odour and comfort requirements in office-type buildings [8]. Diminishing returns are likely to be experienced at rates significantly above 10 l/s p [8]. If air quality problems still persist, the cause is likely to be poor outdoor air quality (e.g., the entrainment of outdoor traffic fumes), poor air distribution or the excessive release of avoidable pollutants into space. However, the energy efficiency of ventilation can be improved by introducing exhaust air heat recovery, ground pre-heating, demand controlled ventilation, displacement ventilation and passive cooling [8]. In each case, a very

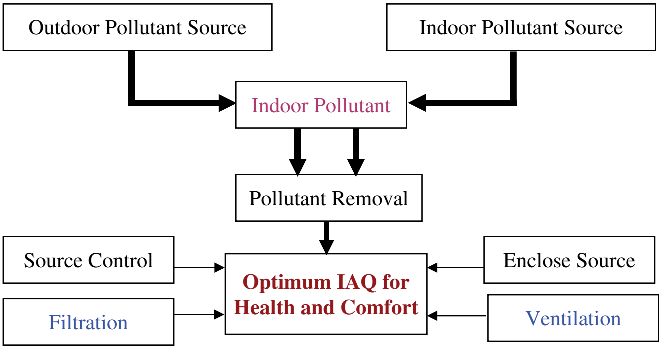


Fig. 5. Strategies for controlling IAQ [8].

careful analysis is necessary to ensure that the anticipated savings are actually achievable. Also, it is essential to differentiate between avoidable and unavoidable pollutant emission s. Achieving energy efficiency and optimum Indoor Air Quality (IAQ) depends on minimising the emission of avoidable pollutants. Pollutants inside buildings are derived from both indoor and outdoor contaminant sources, as illustrated in Fig. 5. Each of these tends to impose different requirements on the control strategies needed to secure good health and comfort conditions. Climate-sensitive and energy-conscious architecture, integrating these strategies, is not only a way of saving money, it primarily provides the occupants with a more humane, valuable environment and insure their well-being by the dynamic and harmonious interaction between man, building and climate.

Innovative daylighting systems have four key aims: to increase daylight levels deep within rooms, to improve daylight uniformity, to control direct sunlight and to reduce glare. In non-domestic buildings, lighting can be a major energy consumer. The provision of daylight therefore needs to be viewed as an important part of low energy, passive solar design. Crisp et al. [9] have identified substantial potential savings (typically around 20–40% of lighting use) from exploiting daylight in such buildings. The four aims of such daylighting systems are therefore to:

(1) increase daylight levels towards the rear of deep rooms,
(2) improve daylight uniformity within a space, and hence its appearance,
(3) control direct sunlight so that it can be used as an effective working illuminant,
(4) reduce glare and discomfort for occupants.

If innovative daylighting systems are to be used for shading, they need to be designed properly. The system should reduce glare for seated occupants, controlling direct sunlight for all sun positions. This is particularly important for interiors with display screen equipment. Supplementary clear view glazing needs extra shading devices.

Laminated glass with light-directing holograms allows a great variety of applications in architecture for utilisation of solar energy, improvement of room comfort as well as design of solar light and colour effects. The angle of diffraction of light depends on the wavelength described by the following equation:

$$\mathrm{Sin}\,\alpha = \lambda/g, \tag{4}$$

where λ is the wavelength of light, g the constant of grating and α the angle of diffraction.

The environmental advantages are obvious. Daylighting in buildings can be improved and reductions in electricity for room illumination will be more than 50% [9]. Shading of direct solar radiation in combination with photovoltaic power generation and diffuse daylighting opens a wide field of future developments and applications.

9. Health and the built environment

Two opposing trends threaten engineers. The first is concern for global pollution. Not only energy use but also energy sources will be defined in terms of atmospheric contamination. The second is a demand for a performance specification for a more satisfy indoor climate. The engineers of today are facing two kinds of environmental forces. The first is a respect for the global external environment, which knows no natural boundaries and is now near saturation with pollution and may be affecting our climate in a harmful way. The second is a rising expectation of better indoor conditions, which in the past has meant a more energy intensive building through air conditioning. Safety issues and avoidance of exposure to toxic materials are being reinforced by concern for long-term health and welfare. The second trend is the continued increase in energy use as our population rises and our productivity increases. Rising standards of living require more fuel to keep us cleaner and warmer and enable us to travel long distances for recreation. More effective use of energy is now essential.

The four more important types of harm from man's activities are global warming gases, ozone destroying gases, gaseous pollutants and microbiological hazards (Table 3). The earth is some 30 °C warmer due to the presence of gases but the global temperature is rising. This could lead to the sea level rising at the rate of 60 mm each decade with the growing risk of flooding in low-lying areas (Fig. 6). At the United Nations Earth Summit at Rio in June 1992 some 153 countries agreed to pursue sustainable development [10]. A main aim was to reduce emission of carbon dioxide and other greenhouse gases. Reduction of energy use in buildings is a major role in achieving this. Carbon dioxide targets are proposed to encourage designers to look at low-energy designs and energy sources (Fig. 7).

Table 3
The external environment

Damage	Manifestation	Design
NO_x, SO_x	Irritant	Low NO_x burners
	Acid rain land damage	Low sulphur fuel
	Acid rain fish damage	Sulphur removal
CO_2	Global warming	Thermal insulation
	Rising sea level	Heat recovery
	Drought, storms	Heat pumps
O_3 destruction	Increased ultra violet	No CFC's or HCFC's
	Skin cancer	Minimum air conditioning
	Crop damage	Refrigerant collection
Legionnellosis	Pontiac fever	Careful maintenance
	Legionnaires	Dry cooling towers

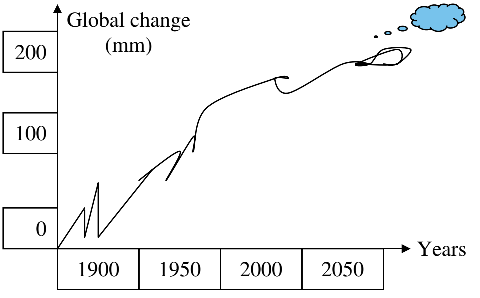


Fig. 6. Change in global sea level.

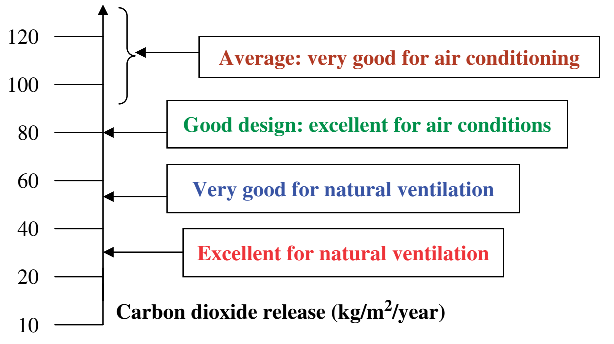


Fig. 7. Designing for atmospheric pollution.

As our knowledge of satisfactory conditions develops so we can control the physical environment to provide satisfaction. Performance-based design will specify how many shall be satisfied. Target figures suggest satisfaction for 90% of the occupants is high quality, down to 70% for poor quality designs. Such performance values are being applied to a whole range of indoor factors such as air quality (Fig. 8), thermal comfort, and noise levels.

10. Comfort temperatures and climate

Nearly half the world's energy use is associated with providing environmental conditioning in buildings and about two thirds of this is for heating, cooling and mechanical ventilation. Whilst in cooler climates, the energy used for heating has been reduced by the application of conservation technologies; energy requirements for cooling are on the increase. The application of passive cooling techniques to buildings in warm climates creates the need for appropriate comfort criteria. The perceived need for mechanical cooling is to achieve accepted standards of thermal comfort, usually defined (directly or indirectly) by temperature limits. There is, however, growing controversy as to what these standards are. For example, in a compilation of results from 47 field studies, predominantly in warm and hot climates, Humphrey's (1978) [11] found that the preferred comfort temperature in buildings was a function of the average monthly outdoor temperature:

$$T_n = 0.534\,T_0 + 11.9, \tag{5}$$

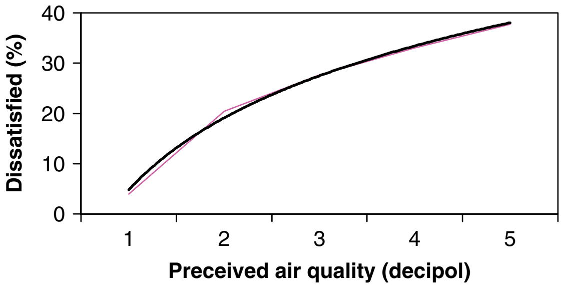


Fig. 8. Designing to a satisfaction level.

where T_n is the indoor comfort temperature, and T_0 is the mean of the local daily maximum and daily minimum outdoor temperatures at the appropriate season of the year.

Fanger's theory [12] relates the sensation of hot or cold (Predicted Mean Vote, PMV), and subsequently the discomfort or dissatisfaction (Predicted Percentage Dissatisfied, PPD), to the imbalance between the heats produced by the bodies' metabolism, and the heat loss to the environment. Obviously this imbalance cannot exist indefinitely, and the sensation of discomfort is a signal to the person to take some action to restore heat balance

$$\mathrm{PMV} = (0.303\exp^{-0.36M} + 0.028)(M - H) \tag{6}$$

and

$$\mathrm{PPD} = 100 - 95\exp-(0.0335\,\mathrm{PMV}^4 + 0.218\,\mathrm{PMV}^2), \tag{7}$$

where M is the metabolic rate and H is the heat loss to the environment.

The result of using Fanger's equations seems to predict the need for much more closely controlled conditions than one usually finds in free-running buildings, in which people still seem to be comfortable. For example the ISO 7730, based upon Fanger's equations, recommends an optimal operative temperature of $24.5 \pm 1.5\,^{\circ}\mathrm{C}$ for light sedentary work with light summer clothing.

11. Natural ventilation

As passive means of ventilating commercial buildings is currently being more seriously considered than in the last few decades, there is a need for an objective assessment of such systems. Too much reliance on air-conditioning will increase CO_2 emissions but excessive outdoor airflow due to inadequately designed or controlled passive ventilation systems can also increase the CO_2 emissions. On the other hand, too little outdoor air can have a serious effect on the indoor air quality whereas too much outdoor air can cause draught and discomfort.

The natural ventilation methods that are most suited to a particular building can only be arrived at by a careful consideration of a number of factors such as:

- depth of space with respect to ventilation openings;
- ceiling height;
- thermal mass exposed to the space;

- location of building with respect to environmental pollution sources, e.g., traffic noise, air pollution, etc.;
- heat gain.

The most widely used methods are given below.

11.1. Single-sided ventilation

This is usually the simplest form of naturally ventilating a building whereby a simple opening in the form of a window or a ventilation device such as a trickle vent on a wall is used to allow outdoor air to enter the building and room air to leave either from the same opening or from another opening situated on the same wall. Although this is a very common and inexpensive system it is uncontrollable, except in an open or a closed position, and can only be effective over a distance of 6 m from the opening itself. Furthermore, some single-sided openings, e.g., windows, are only suitable in moderate climates and are not suitable for winter ventilation.

11.2. Cross-flow ventilation

For spaces of more than 6 m deep two-sided or cross-flow ventilation will be required. This usually implies using the same openings as those used for single-sided ventilation systems but these are installed on two or more opposite walls. These methods can be used for a depth of up to 12 m more favourable for providing larger airflow rates hence more suitable for larger heat gains. However, this method also suffers from the same problems airflow control as the previous method.

11.3. Mixed-flow ventilation

For very large spaces or buildings with large heat gains ($>30\,W/m^2$ of floor area), such as atria or large public halls, more complex systems are required to increase the airflow rate from outside. In such buildings the height of the roof is utilised for situating exhaust air openings to provide a large height to increase the effect of buoyancy. The air inlet openings are situated on the floor, in the case of a suspended floor, or on the walls at low level. With adequate design, these systems can be very effective and are more controllable than the other two methods. However, they require a high ceiling to be viable, i.e., in excess of 4 m.

12. Air movement in buildings

Natural ventilation is now considered to be one of the requirements for low-energy building designs. Until about three decades ago the majority of office buildings were naturally ventilated. With the availability of inexpensive fossil energy and the tendency to provide better indoor environmental control, there has been a vast increase in the use of air-conditioning in new and refurbished buildings. However, recent scientific evidence on the impact of refrigerants and air-conditioning systems on the environment has promoted the more conscious building designers to give serious considerations to natural ventilation in non-domestic buildings [13]. Two major difficulties that a designer has to resolve are the

questions of airflow control and room air movement in the space. Because of the problem of scaling and the difficulty of representing natural ventilation in a laboratory, most of the methods used for predicting the air movement in mechanically ventilated buildings are not very suitable for naturally ventilated spaces [13]. However, computational fluid dynamics (CFD) is now becoming increasingly used for the design of both mechanical and natural ventilation systems. Since a CFD solution is based on the fundamental flow and energy equations, the technique is equally applicable to a naturally ventilated space as well as a mechanically ventilated one, providing that a realistic representation of the boundary conditions are made in the solution.

Flow equations:

Wind:

The volume flow rate (Q) through a large opening is given by Bernoulli's equation:

$$Q = C_{\mathrm{d}} A_0 \sqrt{\frac{2\Delta p}{\rho}}, \tag{8}$$

where C_{d} is the discharge coefficient of the opening, A_0 is the area, ρ is the air density and Δp is the pressure difference across the opening, which is given by:

$$\Delta p = 0.5 \rho V_{\mathrm{r}} C_{\mathrm{p}}, \tag{9}$$

where V_{r} is the reference wind speed and C_{p} the pressure coefficient at the opening.

For more than one opening in parallel:

$$C_{\mathrm{d}} A_0 = \sum_{i=1}^{n} (C_{\mathrm{d}} A)_i. \tag{10}$$

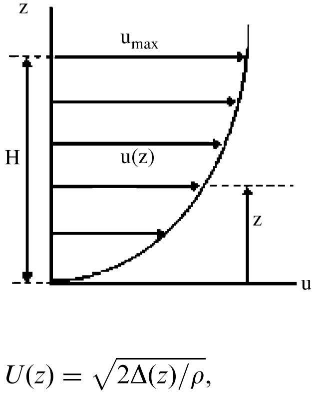
And for more than one opening in series:

$$\frac{1}{(C_{\mathrm{d}} A)^2} = \sum_{i=1}^{n} \frac{1}{(C_{\mathrm{d}} A_0)_i^2}. \tag{11}$$

The pressure difference due to temperature difference across a large opening is:

$$\Delta p(z) = \Delta \rho g z \tag{12}$$

where Δp is the difference in density across the opening, z the height between two openings and g the acceleration of gravity.



Also:

$$U(z) = \sqrt{2\Delta(z)/\rho}, \tag{13}$$

Hence:

$$U(z)\alpha z^{1/2}, \tag{14}$$

and

$$\frac{U(z)}{U_{\max}} = \left(\frac{z}{H}\right)^{1/2}. \tag{15}$$

The mean velocity (U) through an opening of height (h) is

$$U = \frac{U_{\max}}{H^{1/2}} \int z^{1/2}\,\mathrm{d}z = \frac{U_{\max}}{H^{1/2}} \frac{2}{3} H^{1/2} = \frac{2}{3} H U_{max}. \tag{16}$$

The volume flow rate through the opening (Q) is

$$Q = C_{\mathrm{d}} w U = \frac{2}{3} C_{\mathrm{d}} w H U_{\max} = \frac{2}{3} C_{\mathrm{d}} A U_{\max}, \tag{17}$$

Where w is the width of the opening.

Buoyancy:

The volume flow rate though a large opening due to temperature difference is given by:

$$Q = \frac{C_{\mathrm{d}}}{3} A U_{\max}, \tag{18}$$

However, in a buoyancy-driven flow, the equal masses of air enter and leave through the same opening. If H is the total height of the opening, then the influx or efflux flow is:

$$Q = \frac{C_{\mathrm{d}}}{3} \sqrt{\frac{gH\Delta T}{T}}, \tag{19}$$

where ΔT is the temperature difference across the opening and T is the mean temperature (K). The room dimensions are $12\,\mathrm{m} \times 10\,\mathrm{m} \times 2.5\,\mathrm{m}$ and have four openable windows of height 2 m and width 1 m on each of the 12 m walls, as shown in Fig. 9.

The acceptable conditions can be achieved for typical summer and winter climates by opening windows or using trickle ventilators. However, the flow rates through windows openings, due to wind in cross-ventilation and buoyancy in single-sided ventilation. For wind-driven flow, the difference was attributed to the values of reference wind speed and pressure coefficients, which have been used in the formula. For the buoyancy-driven flow however, this was due to the velocity profile through an opening.

One of the primary considerations in the design of natural ventilation systems is the geographic location of the building. This will determine the seasonal variations in the external environmental parameters, viz air temperature, solar radiation, wind, humidity and outdoor air quality. Natural ventilation systems are normally specified for steady airflow through the openings, however transient effects such as wind turbulence could cause large fluctuations in the airflow through the openings. To allow for these effects will require rigorous analysis and they are not normally considered in great detail for ventilation system design. Other considerations that influence natural ventilation design are the exposure of the building to the wind, rain and the sun. Most meteorological data is for open country at a reference point on or from the ground. However, buildings and other obstructions can distort the wind flow and adjacent buildings in particular causing shielding from the wind, rain and the sun. Therefore, meteorological data should be adequate to take these effects into consideration.

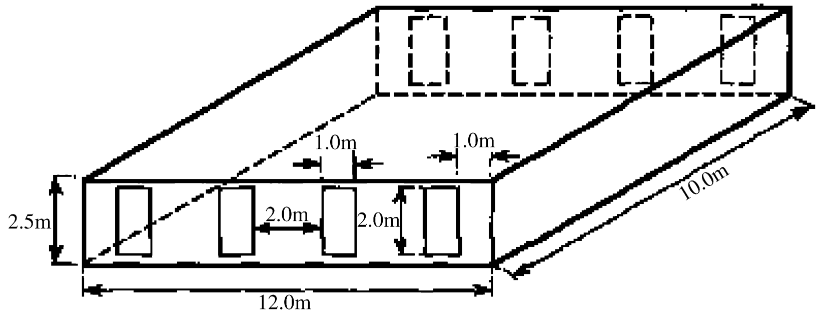


Fig. 9. Room dimensions.

The form and height of the building have major influences on any natural ventilation strategy that is considered by a designer. Such factors as ceiling height and depth have already been mentioned, but the height of the building is also significant. Traditionally, high-rise buildings have not been considered for natural ventilation apart from a few exceptions. This is due to the large buoyancy pressures between low-level and high-level openings and also the greater wind effect on the high-level openings. If natural ventilation is to be contemplated for high-rise buildings, sophisticated control for the ventilation openings is essential for the system to function effectively. Other considerations such as thermal mass and building materials can have an influence on the performance of natural ventilation systems, particularly if this is integrated with a night cooling systems.

The purpose of ventilating a building is to provide clean outdoor air to the occupants and to remove excessive heat from inside the building. Therefore, the ventilation loads of a building are both thermal and pollution. Thermal loads are due to heat loss or gain by conduction through the fabric, solar gain, internal gain due to occupancy, lighting, equipment, etc. Pollution loads are normally the bioefficient produced by the occupants, volatile organic compounds (VOC) emitted by building materials and furnishing and VOC's and other gases and vapours such as H_2O, O_3, CO_2, CO, NO_x produced by equipment, cleaning agents and domestic and industrial process. A good ventilation system must be effective in dealing with thermal loads and controlling indoor pollutants to below threshold limit values [14].

Solar-induced ventilation can provide adequate airflow rates to naturally ventilated buildings for extracting moderate thermal and pollution loads. However, large loads can only be removed if solar ventilation systems are designed to utilise the wind pressure or if they are coupled with mechanical systems. Such ventilation systems offer the advantage of better control (manual or automatic) than is achievable with conventional methods such as windows and, they are therefore, more suitable for ventilating modern buildings.

13. Energy savings

The admission of daylight in buildings alone does not guarantee that the design will be energy efficient in terms of lighting. In fact, the design for increased daylight can often raise concerns relating to visual comfort (glare) and thermal comfort (increased solar gain in the summer and heat losses in the winter from larger apertures). Such issues will clearly need to addressed in the design of the window openings, blinds, shading devices, heating

systems, etc. Simple techniques can be implemented to increase the probability that lights are switched off [15]. These include: (1) making switches conspicuous (2) locating switches appropriately in relation to the lights (3) switching banks of lights independently, and (4) switching banks of lights parallel to the main window wall.

Large energy savings cover a wide range of issues including:

- guidelines on low energy design;
- natural and artificial lighting;
- solar gain and solar shading;
- fenestration design;
- energy efficient plant and controls;
- examining the need for air conditioning.

The strategy:

- Integration of shading and daylighting: an integral strategy is essential and feasible where daylighting and shading can be improved simultaneously.
- Effect of shading on summer comfort conditions: solar shading plays a central role in reducing overheating risks and gives the potential for individual control, but should be complimented with other passive design strategies.
- Effect of devices on daylighting conditions: devices can be designed to provide shading whist improving the daylight conditions, notably glare and the distribution of light in a space, thus improving the visual quality.
- Energy savings: energy savings from the avoidance of air conditioning can be very substantial, whilst daylighting strategies need to integrated with artificial lighting systems to be beneficial in terms of energy use.

The energy potential of daylighting is thus inextricably linked with the energy use of the associated artificial lighting systems and their controls. The economics of daylighting are not only related to energy use but also to productivity. Good daylighting of workspaces helps to promote efficient productive work, and simultaneously increases the sense of well-being. However, energy and economics should not become the sole concern of daylighting design to the exclusion of perceptual considerations.

The following initial requirements for the air quality in the archives were established by the consultant in conservation and international recommendations (BSI 5454: 1989) [16]:

- air temperature between 17 and 19 $^{\circ}$K;
- relative humidity between 50 and 60%, with lower values in the photographic archives;
- low levels of natural light and total exclusions of direct sunlight in archives, reading-rooms and complementary spaces;
- exclusion of ultra-violet radiation from natural and artificial lighting;
- air filters to exclude particles larger than 0.01 μm (this requirement was relaxed, considering the high cost, additional energy requirements and problems of maintenance);
- filters of active carbon to reduce the content of ozone, sulphur dioxide and oxides of nitrogen.

14. Use and management of passive solar environments

The objectives of passive solar design are often at variance with subsequent energy performance. The benefits of passive solar design may be considered within the context of three basic types of environment. First, there are design measures that can improve the environmental conditions in the 'External Areas', through the provision of open courts and courtyards, lightwells, shelterbelts and microclimatically protected areas generally. Second, there are design measures concerning the provision of enclosed 'Intermediate Areas' such as sunspaces, conservatories, glazed streets, covered courts and atria. Finally, there are passive solar design measures relating to the 'Internal Areas' within a building. These measures aim to reduce dependency on purchased energy in those areas of a building that are subject to occupation throughout the year, and can result in improved environmental quality overall. Occupants can impact upon energy performance through their actions in each or all of the five areas illustrated in Fig. 10.

The activities and operations of the occupants, their patterns of use and misuse, can have a significant effect on the energy performance of the intermediate and internal environments. The management and control of three interfaces shown in Fig. 10: external to internal, external to intermediate, and internal to intermediate can also have significant effect particularly in response to seasonal, daily and hourly variations in solar energy availability, its regulation and distribution. Other facilities management function can also have major energy implications, particularly maintenance, cleaning, replacement, refurbishment and adaptation.

The benefits of passive solar environments include:

- reductions in non-renewable energy consumption and CO_2 emission;
- savings in the cost of purchased energy generally;

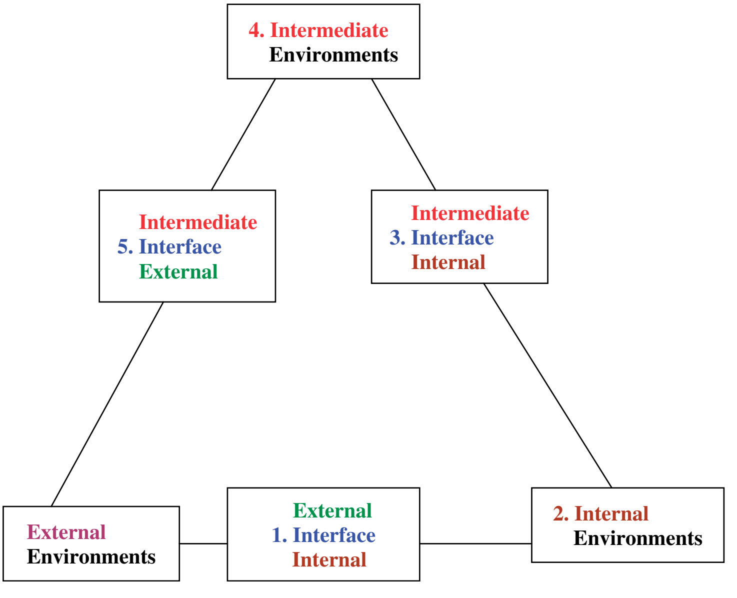


Fig. 10. Areas of user impact.

- savings in space and water heating costs;
- amenity and social benefits to occupants;
- prestige benefits to organisations;
- natural environment benefits for individual users;
- improved human comfort, well-being, and performance.

The potential risks that are commonly associated with passive solar environments include:

- increased purchased energy consumption through inappropriate use;
- seasonal overheating;
- unacceptable temperature fluctuations;
- poor air quality and condensation;
- unacceptable lighting variation and glare;
- temperature stratification;
- thermal fatigue and fracture of materials;
- winter survival of plants.

In practice, low-energy environments are achieved through a combination of measures that include:

- the application of environmental regulation and policy;
- the application of environmental science and best practice;
- mathematical modelling and simulation;
- environmental design and engineering;
- construction and commissioning;
- management and modifications of environments in use.

Integrated energy systems need to be implemented at two levels:

(1) Integration of various thermal energy sources into concurrent systems for heating, cooling and production of hot water.
(2) Physical integration of such systems into the building structure.

However, integrated energy systems for buildings face a number of barriers, of which the most significant are:

- lack of expertise, information and demonstration systems;
- immature products and service delivery chains;
- utilities that still favour central generation and the market power created by such infrastructure;
- electricity markets that do not yet account for environmental externalities.

The storage concept is based on a modular design that will facilitate active control and optimisation of thermal input/output, and it can be adapted for simultaneous heating and cooling often needed in large service and institutional buildings. Such a system can be illustrated as shown in Fig. 11 conceptual integration of various warm/cold energy sources combined with thermal energy storage.

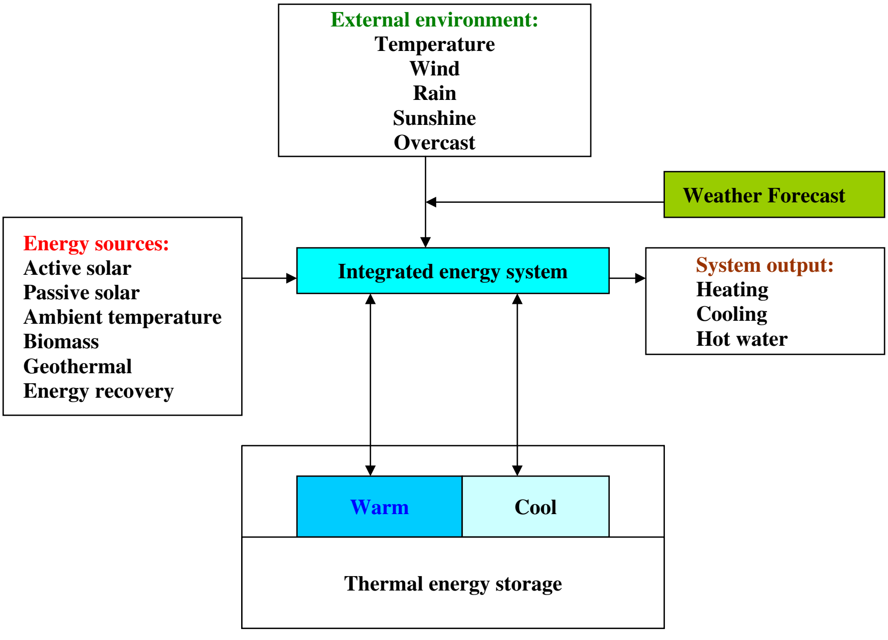


Fig. 11. Conceptual illustration of an integrated energy system with thermal storage.

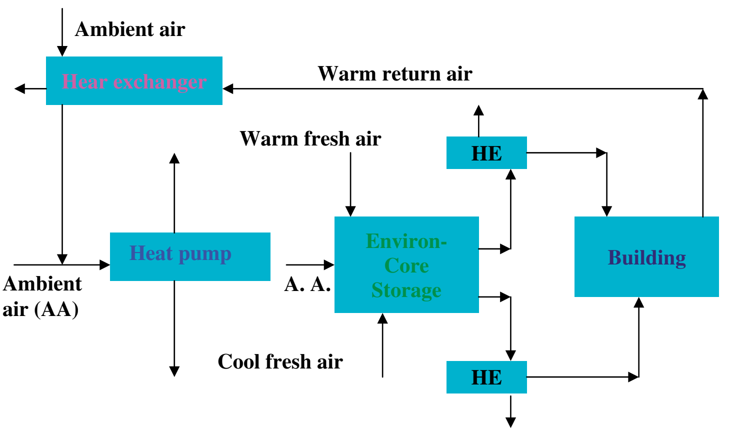


Fig. 12. Flow sheet of combined heating and cooling with air-source heat pump and energy recovery from return air in combination with Environ-core thermal storage.

A main core with several channels will be able to handle heating and cooling simultaneously, provided that the channels to some extent are thermally insulated and can be operated independently as single units, but at the same time function as integral parts of the entire core. The shapes and numbers of the internal channels and the optimum configuration will obviously depend on the operating characteristics of each installation some possible configuration are shown in Fig. 12. Loading of the core is done by diverting warm and cold air from the heat pump through the core in periods with excess capacity

compared with the current need of the building. The cool section of the core can also be loaded directly with air during night, especially in spring and fall when nights are cold and days may be warm.

In summary, achieving low-energy building requires comprehensive strategy that covers, not only building designs, but also considers the environment around them in an integral manner. Major elements for implementing such a strategy are as follows.

(1) efficiency use of energy
- climate responsiveness of buildings;
- good urban planning and architectural design;
- good house keeping and design practices;
- passive design and natural ventilation;
- use landscape as a means of thermal control;
- energy efficiency lighting;
- energy efficiency air conditioning;
- energy efficiency household and office appliances;
- heat pumps and energy recovery equipment;
- combined cooling systems;
- fuel cells development.

(2) Utilise renewable energy
- photovoltaics;
- wind energy;
- small hydros;
- waste-to-energy;
- landfill gas;
- biomass energy;
- biofuels.

(3) Reduce transport energy
- reduce the need to travel;
- reduce the level of car reliance;
- promote walking and cycling;
- use efficient public mass transport;
- alternative sources of energy and fuels.

(4) Increase awareness
- promote awareness and education;
- encourage good practices and environmentally sound technologies;
- overcome institutional and economic barriers;
- stimulate energy efficiency and renewable energy markets.

15. Conclusions

Many cities around the world are facing the problem of increasing urban density and energy demand. As cities represent a significant source of growth in global energy demand, their energy use, associated environmental impacts, and demand for transport services create great pressure to global energy resources. Low-energy design of urban environment and buildings in densely populated areas requires consideration of a wide range of factors,

including urban setting, transport planning, energy system design, and architectural and engineering details. It is found that densification of towns could have both positive and negative effects on the total energy demand. With suitable urban and building design details, population should and could be accommodated with minimum worsening of the environmental quality.

References

[1] Martin W. Air quality control in commercial buildings. WREC; 1996.
[2] Limb MJ. Air intake positioning to avoid contamination of ventilation. AIVC; 1995.
[3] Erlich P. Forward facing up to climate change. In: Wyman RC, editor. Global Climate Change and Life on Earth. London: Chapman & Hall; 1991.
[4] Miller G. Resource conservation and management. California: Wadsworth; 1990.
[5] ASHRAE. Energy efficient design of new building except new low-rise residential buildings. BSRIASHRAE proposed standards 90-2P-1993, alternative GA. USA: American Society of Heating, Refrigerating, and Air Conditioning Engineers Inc., 1993.
[6] Molla M. Air pollutants and its probable transmutation in the ionosphere. Renew Energy 1997;10 (2/3):327–9.
[7] Bahadori M. A passive cooling/heating system for hot arid regions. In: Proceedings of the American Solar Energy Society Conference, Cambridge. Massachusetts, 1988. p. 364–7.
[8] Lobo C. Defining a sustainable building. In: Proceedings of the twenty third national passive conference. American Solar Energy Society (ASES'98). Albuquerque: USA; 1998.
[9] Crisp V, Cooper I, McKennan G. Daylighting as a passive solar energy option: an assessment of its potential in non-domestic buildings. Report BR129-BRE. Garston, UK, 1988.
[10] Horning M, Skeffington R. Critical loads: concept and applications. Institute of Terrestrial Ecology. London: HMSO; 1993.
[11] Humphrey's M. Outdoor temperatures and comfort indoor. Building Res Pract 1978;6(2).
[12] Fanger P. Thermal comfort: analysis and applications in environmental engineering. Danish Technical Press; 1970.
[13] Fordham M. Natural ventilation. Renew Energy 2000;19:17–37.
[14] Awbi H. Ventilation of buildings. London: Spon; 1991.
[15] Givoni B. Man climate and architecture. London, UK: Applied Science Publisher Ltd; 1976. p. 289–306.
[16] BS 5454. Storage and exhibition archive documents. London: British Standard Institute; 1989.